OSL Calibration Standards
For the MSA

This document discusses construction of OSL calibration standards for use to 1 GHz. We will focus on standards mounted on SMA connectors, but similar principles apply to other connector types.

Mating Planes and Reference Planes

The first thing to understand is where the calibration occurs, and what is actually your standard. In Figure 1, a standard with a female connector connects to a male SMA connector that is either mounted on the reflection test fixture, or may be at the end of a cable leading from the MSA. The same principles will apply if the connectors are reversed.

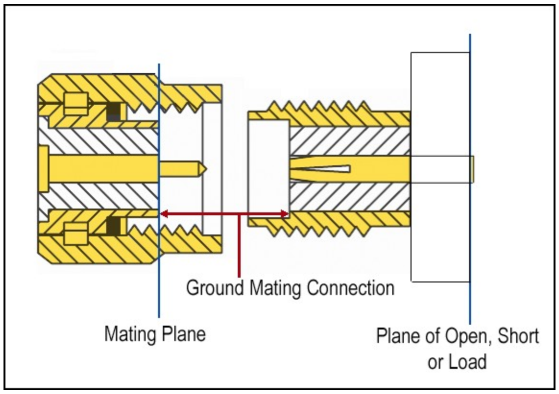


Figure 1—Mating of SMA Connectors
Red arrow shows the small surface that makes the
true ground connection to maintain the coaxial structure.

Both the male (plug) and female (jack) SMA connectors are internally coaxial structures filled with Teflon dielectric, whose ratios of inner conductor diameter to outer conductor diameter (actually the inner diameter of the outer conductor) establish the desired 50 ohm impedance. When not mated, the coaxial structure of each comes to an abrupt end. When mated, the inner conductors combine to form a continuous conductor with no change in size at the point of mating, and the outer conductors meet to form a continuous outer shield, also with no step discontinuity. The red arrows in Figure 1 show the surfaces that must meet in order to form such a continuous shield. While the threaded portions also make electrical contact, it is the inner portions that form the critical connection. With the two halves joined, the Mating Plane in Figure 1 shows where one connector ends and the other begins, as far as electrical signals are concerned.

In this case, the female connector contains the Open, Short or Load used for calibration. Those are located in a plane a short distance away from the Mating Plane. One of these planes will become the Reference Plane. The significance of the Reference Plane is that everything from that plane back to the test fixture is effectively part of the fixture. Everything from the Reference Plane to the DUT is effectively part of the DUT. To put it another way, when we measure reflection or impedance, we are measuring what the reflection or impedance is when viewed from the Reference Plan looking toward the DUT.

If we are going to be testing DUTs soldered on the back of connectors, then the plane in which the Short is made, on the connector backside, is the desired Reference Plane. If we are going to be attaching an antenna with a cable, and want to know the impedance viewed from the beginning of the cable, then we want the Mating Plane to be the Reference Plane. Specifying which plane we are using is a matter of defining exactly what our calibration standard really is.

When we perform a test, everything to the right (in our diagram) of the Reference Plane is the true DUT. Likewise, when we calibrate, everything to the right of the Reference Plane is the true calibration standard. To use the connector backside as the Reference Plane, we would say our Short, for instance, consists of a piece of brass and has a time delay of zero, because it occurs at the Reference Plane. If the Mating Plane is to be the Reference Plane, then our Short actually consists of a female connector with a piece of brass on the back, and the actual shorting occurs some distance (measured as time delay) away from the Reference Plane.

Some would define a "Calibration Plane" to be the plane where the "standards" (meaning the shorting plate in the case of the Short) are mounted, but the term Calibration Plane is often used synonymously with Reference Plane. I think it is best to say that the standard is always mounted at the Reference Plane; it is merely a question of whether the Short standard is just the shorting mechanism itself (so the Reference Plane is the connector backside), or is the shorting mechanism mounted on the back of a connector (so the Reference Plane is the Mating Plane). You define what the standard is by specifying the delay from the Mating Plane to the actual open circuit or shorting mechanism. (Delay is irrelevant to the Load).

In the MSA calibration dialog for OSL, it is possible to specify certain characteristics of the standards:

1. The Open—We may specify the time delay of the Open; i.e. the delay from the Open to the actual end of the center conductor. In addition, any abruptly ending coax cable has some amount of fringe capacitance at that end, which we may specify. As just discussed, the time delay of the Open depends where we want the Reference Plane. If we want it at the backside of the right connector, the delay is zero, because that is exactly where the open circuit occurs.

2. The Short—We may also specify the time delay of the Short, which is normally the same as for the Open. In addition, real-world Shorts experience some loss due to skin effect, which we can specify as a series resistance in parallel with an inductance.

3. The Load—We specify only the resistance of the Load. Normally, the Load is 50 ohms mounted on a 50-ohm connector. In theory, this looks like exactly 50 ohms whether you are looking at the resistor from the Mating Plane or the backside of the Load connector, so it is not necessary to specify a delay. Note that the Load is commonly thought of as matching the reference impedance of the bridge or other fixture to which it is attached. But what is really important is that it match the characteristic impedance of the connector on which it is mounted. It is possible to use a 49.9 ohm resistor and get reasonable accuracy, 75 ohms is not a good idea, unless mounted on a 75 ohm connector.

When we construct the Open, Short and Load standards, we are working at the plane on the back side of the connector, as shown at the right side of Figure 1. For the Open, we simply end the center conductor at the connector backside. For the Short or Load, we attach the shorting material or the 50-ohm load at the connector backside. We place the resistors upside down to put their conductive surface near the Teflon, in the same plane as the Short. But that is probably not critical if we actually measure the S-parameters of the standards, as discussed below.

Some SMA connectors and adapters suitable to calibrating the MSA are shown at the end of this document. They are from the Amphenol RFX family, and are relatively inexpensive. Specifications for the Open and Short with these connectors are built into the MSA software.

In the simplest case, we would just ignore the difference between the front and back planes of the connector. This would work fine at low frequencies where the phase delay is far less than one degree. The next better approach would be to measure the distance between the two planes and calculate the time delay, using HP AppCad or similar software to determine the rate of propagation through a coax with Teflon dielectric. That would probably be reasonably accurate for frequencies below 1 GHZ. The best approach is to take advantage of the fact that there are better VNAs around than ours, and use one of them to measure the actual characteristics of the calibration standards, in the form of S-parameters.

We have tested the RFX connectors and builders may use the results of those tests. The two main variables in this approach are the length of the connectors and the exact placement of the open/short/load on the back of the connectors. It appears that manufacturing tolerances for length are not a major issue in our frequency range. The length tolerance is probably on the order of a few mils. At 1 GHz the phase delay through a connector is roughly 0.05 degrees per mil. At 100 MHz it is only 0.005 degrees per mil.

The bigger variation is in construction details. For example, the Open may end flush with the connector backside, or may project a few mils further. The Short will be a flat piece of sheet metal soldered to the connector, and its exact location depends on how flush it is to the connector body. Altogether, we should probably anticipate that there may be up to 10 mils of variation in the location of the backside connections. This means 0.05 degrees of error at 100 MHz, and 0.5 degrees at 1 GHz. Since we measure reflection with these standards, there is a two-way travel path, which means we have to double these phase errors. Given the many other phase issues at high frequency, such as change in phase from cable flexing or from temperature changes, these numbers are perfectly acceptable.

There is one more calibration standard that we have not yet mentioned—the Through standard—that is used for calibration of Transmission mode measurements when a bullet or barrel adapter is needed. This one also depends on the DUT, which now will have two cables leading to it. If the DUT requires one male and one female connector, we do the Through calibration by directly connecting the two cables from the VNA, and we don’t even need a Through standard. In other cases, we may need to connect the cables with a barrel (two male plugs, for attaching to female cable ends) or a bullet (two female jacks, for attaching to two male cable ends). So we also need to select barrel and bullet adapters as calibration standards. In this case, there is no need for any physical modification to the standards. In the calibration process, we need to remove the effect of the length of the adapters, which we do by measuring and specifying the time delay caused by the adapter.

Construction of the Calibration Standards.

The SMA connectors that were selected for use in construction of calibration standards are shown in Appendix A. They are all Amphenol connectors available from Digi-Key. The PCB-mount styles are about $3.50 each, on the inexpensive end of the range for such connectors. The bullet and barrel are $5-6 each, also on the inexpensive end. Three of each of the PCB-mount styles are needed, and one each of the bullet and barrel. There are cheaper connectors available that would be suitable for someone who can measure his/her own standards on a VNA. However, to assure that different builders use exactly the same connectors with no hidden change in specs, it is best to settle on the Amphenol connectors, or some other commonly available connector. The two Amphenol RFX connectors have a limited frequency range, which I believe is 2 GHz, as opposed to the 18 GHz common for SMA connectors in general. That cuts their price in half and is plenty for our purposes.

Of course, not all DUTs have SMA connectors, so other standards might be necessary. To deal with N and BNC connectors, the least expensive approach is to select two adapters of each type, one converting from SMA male to N or BNC female, and the other from SMA male to N or BNC male. If the characteristics of those adapters are measured, then calibration can be done with the SMA standards attached to the adapters. But such adapters are not part of the current project.

Actual Construction

The basic idea of construction of OSL standards is to remove two of the connector legs in order to gain access to the center pin, cut the center pin to the desired length and solder on the short or load resistors. The legs break off cleanly with pliers, but leave the small pedestal on which they sit. That pedestal may need to be filed flush with the connector body, to make it easier to deal with the center pin, which is easily done with a small triangular file. You need to check your work after every few file strokes, to be sure things remain flat and that you have not gone too far. For the Open, the center pin can be cut almost flush with a fine hacksaw or a $5.00 Razor Saw from a hobby store. The pin can then be filed flush. For the Short and Load, it is handy to have the center pin stick up a tiny amount; perhaps half the height of a resistor for the Load, and a bit more for the Short.

The Amphenol RFX connectors actually have a tiny depression around the center pin, so when the center pin is filed flush with the outer part of the connector body, the pin still extends a tiny bit above the floor of the depression. That is not a problem. The idea is to achieve uniformity among different builds, which is done by matching the center pin height to the outer part of the connector body, which the file naturally uses as a guide. The pin height for the Load can be the same as for the Open; that tiny bit of pin sticking up is perfect for aligning the resistors. The height for the Short should be nearly irrelevant as long as it extends through the shorting material to make soldering possible.

The shorting of the Short is accomplished by attaching a small brass square or disc with a hole in the middle to fit over the pin. The easiest way to make the disc is to poke a hole in a thin sheet of brass and then cut around it with a shears. The exact shape does not matter as long as the disc will contact the connector body all the way around.(I actually had the best luck cutting a square piece, and notching the four corners with a Nibbler so I ended up with a cross. The cross fits nicely inside the connector legs, or their stubs, and stays in place while you solder it. The disc can be tinned with solder, fitted over the center pin (after tinning the body of the connector), and soldered in place. (The solder used for tinning will become the actual conductor, but its resistance will be miniscule.) When the top of the disc is heated (which may require a bit of solder for good thermal contact with the soldering iron), the connector body will heat and a pool of solder will form under the entire disc. You need to press down on the disc to get it flush, and hold it while the solder cools, which may take 5-10 seconds. Then solder the center pin to the disc. If a portion of the disc is not flush, press down with a screwdriver tip on the appropriate side of the center pin, and then heat the non-flush area briefly. The screwdriver not only presses the disc in place, but helps prevent the entire disc from melting loose. Getting the brass flush is the most important thing; if you have gaps between the disc or cross and the connector body, bridge them with solder. I actually made one short from copper mesh, all filled in with solder, and it tested as well as any other Short.

The Load is accomplished by soldering two 100-ohm resistors from the center pin to ground. Size 0805 are easiest to deal with, but 0603 is fine. By a stroke of luck, it turns out that if a 100 ohm resistor has about 1.3 nH series inductance, and 0.25 pF capacitance (which are about the right value), the combination of two parallel such resistors not only has the desired 50-ohm resistance, but the inductance and capacitance nearly cancel each other up to at least 1 GHz. With a single 50-ohm resistor, if you could get one, there would be a significant net inductance at 1 GHz.

First, tin the center pin and the connector body of the Load. Add a touch of solder to one end of a resistor. Butt the resistor against the center pin (not on top of it) and solder it in place. In theory, it is best to put it face down, but my tests showed no difference. With the resistor face down, the advantage of having the resistive surface flush with the connector back is offset by increased capacitance from having the conductive surface so close to the connector body. You don’t want a blob of solder that sticks up higher than the resistor. Then solder the other end of the resistor to the connector body. Do the same with the other resistor, oriented 180 degrees from the first.

As discussed above, if the load is 50 ohms of resistance mounted on a 50 ohm connector, the length of the connector is not critical because there is no meaningful reflection. This means the Load connector does not have to match the Open and Short. If you can find a commercial termination that is fairly accurate (many are not), you can use that. If the DC resistance measures very close to 50 ohms, and the Load is rated to several GHz, it is likely to be close to 50 ohms at 1 GHz. Even if is off by a few tenths of an ohm, you can use it and specify its actual resistance when calibrating, though if you have several Loads it may be difficult to keep track of which is which.

Finally comes the shielding. One purpose of leaving two legs on the connectors is to make shielding easier. The Short does not need a shield, but the legs still make nice handles. The shielding may have subtle phase effects on the Load and Open, but is mainly to prevent contamination from handling. I have actually gotten good results covering the load with nail polish. Clear is best, but I have also used red over the top of a layer of clear to identify it as my calibration Load. The colored stuff works fine as long as you don’t have the glitter type—check the ingredients for aluminum powder, which is obviously bad.

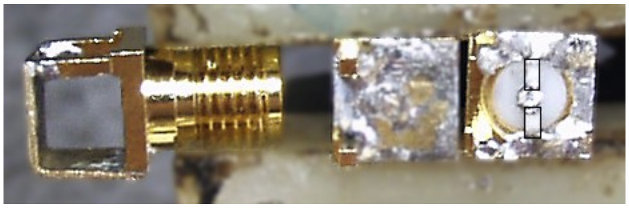


Figure xx—Open, Short and Load.

Open on the left has a piece of ¼” angle added to support shielding.
Short in center has two legs sticking out; remainder is covered
by a small piece of brass sheet with solder splotches on top.
Load on right has two size 0603 100-ohm resistors outlined in black.

Test Results
Below are some test results taken on a commercial VNA. We do not show results for the Open, because they functioned perfectly, with a fixed delay and no attenuation. The Shorts show some loss due to skin effect.

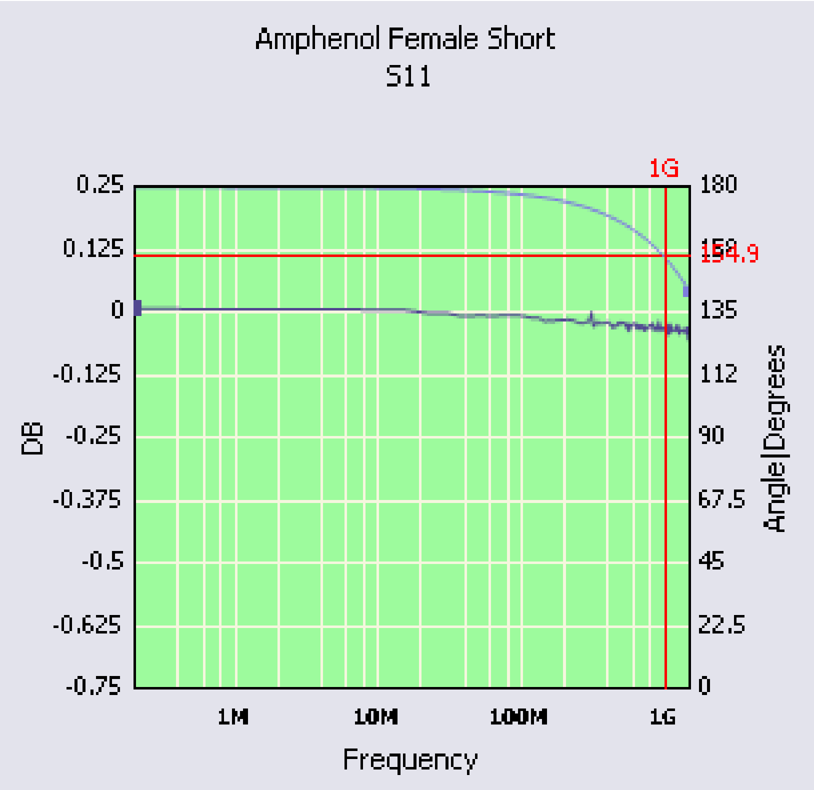


Figure xxx—The skin effect created some dropoff of response.
Dark blue is left axis (DB); light blue is phase

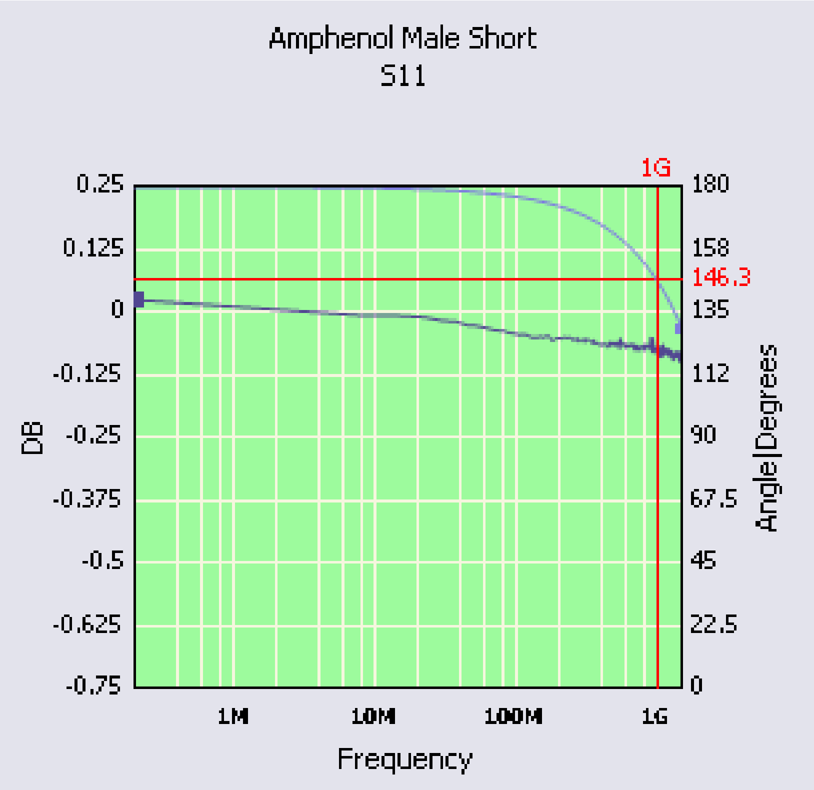


Figure xxx—The skin effect is stronger in the Male connector

(In these tests, the lowest frequency point is unreliable, and the second point does not occur until 7 MHz.) We can compensate pretty well for the skin effect by specifying the Short to have a certain series resistance in parallel with an inductance. At low frequency, the resistor is completely bypassed, and as the frequency increases more and more current is forced through the resistor.

Next are results for a Load made with an Amphenol RFX connector, and one made from a $0.50 connector from Hong Kong.

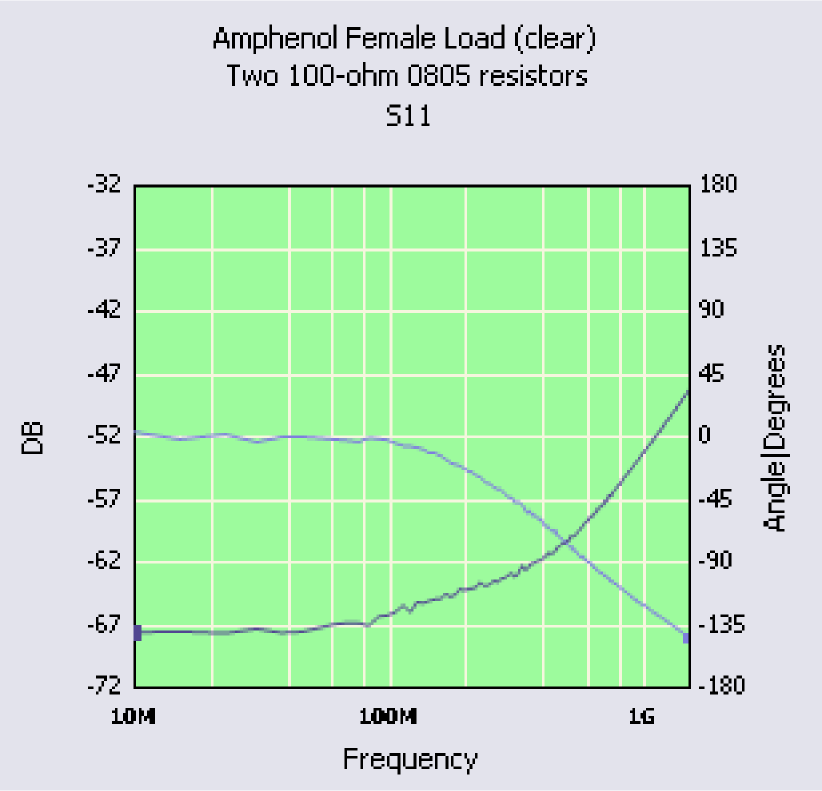


Figure xxx—Amphenol Load

The Amphenol Load is outstanding to 300 MHz and by 1 GHz it still has return loss better than 50 dB, which is quite good.

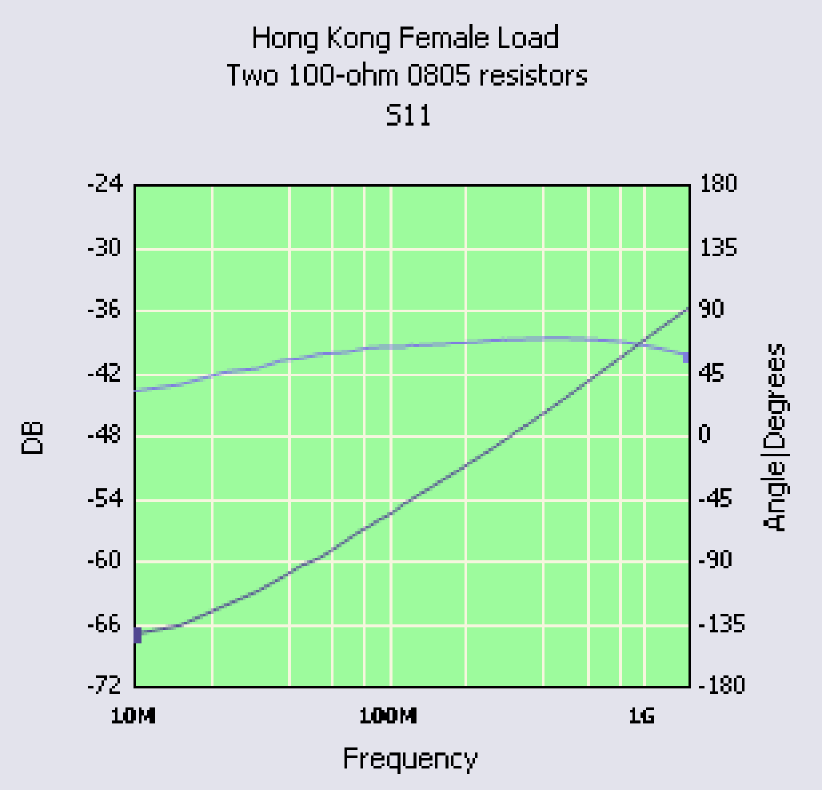
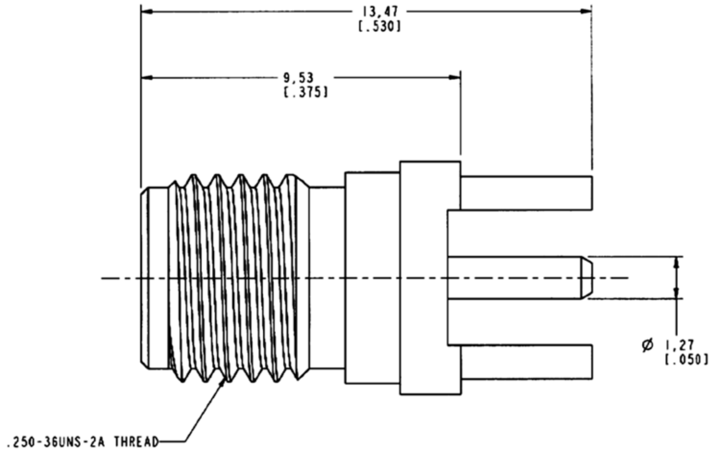


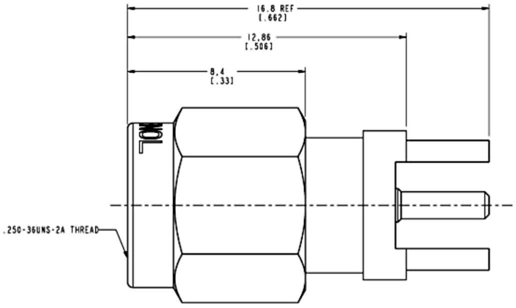
Figure xxx—Load with cheap connector

The cheap connector starts off as good as the Amphenol, but deteriorates rapidly as the frequency increases, reaching about 39 dB at 1 GHz. That is normally a perfectly acceptable return loss, but is not good for calibration purposes. A male connector of the same type was even worse. The cheap connectors were also tested for the Open and Short, and did fine. But they definitely are not suitable for a calibration Load.

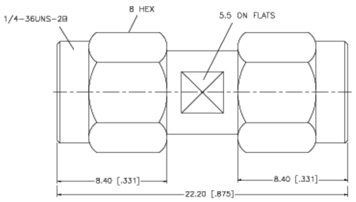
Appendix A--Connectors for Calibration Standards



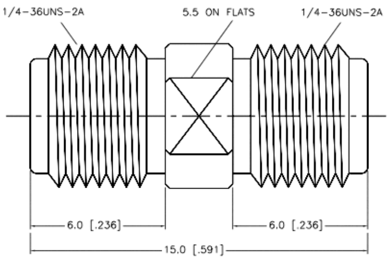
Amphenol 901-144-8RFX



Amphenol 901-9895-RFX



Amphenol Connex 132168



Amphenol Connex 132169